The Optimization of Welding Tool Material and Welding Parameters in Friction Stir Spot Welding of Plastics Using Taguchi Experimental Design

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Abstract- In recent years, friction stir spot welding (FSSW) is widely used as a joining method espically in the automotive industry. This method has been found of use in joining of plastics. The welding parameters and the tool material have very significant effects in FSSW joining. Welding tool material is very important in FSSW because the tool generates heat in welding and cooling rate in the solidification period. In this study, the dependence of the lap shear fracture load on the FSSW welding parameters (tool rotational speed, tool plunge depth, tool dwell time) and different heat transfer coefficient of the welding tool have been investigated. "The highest -the better" quality control characteristic using the Analysis of Variance (ANOVA) method was used to find the optimum welding parameters. The experiments were arranged by using Taguchi"s L16 orthogonal array. The results have been analyzed by the graphical methods and numarical data. The most spectucular result of this study was the effect of tool material on the weld strength. The welding tool heat transfer coefficient and the tool rotation speed were observed very effective and important on FSSW weld strength of high density polyethylene sheets, Finally, the improvement in the weld strength from the initial welding parameters to the optimal welding parameters was found about 22%.

Keywords- Thermoplastics FSSW, Taguchi method, FSSW tool, FSSW welding parameters

1. Introduction

High density polyethylene (HDPE) is widely used as a commodity polymer with high-tonnage production due to its distinctive mechanical and physical properties. Because of its low toughness, weather resistance, and environmental stress cracking resistance as compared to engineering polymers, its application in many areas has been limited. To improve these disadvantages, HDPE has been reinforced with fillers [1]. The critical trend in automotive manufacturing is the increasing use of lightweight alloys in place of traditional steel materials. The use of aluminum alloys, composite materials and plastics for auto body panels leads to a reduction in the vehicle body weight which translates into reduced emissions and increased performance. After the body panels are formed into the desired shapes they will require joining to other parts of the automobile [2]. Resistance spot welding (RSW) is a very common joining technique in the automotive industry [3]. The RSW is widely used in the joining of sheet metal assemblies due to its advantages in welding efficiency and suitability for automation [4]. The joining of light metals and aluminum were experienced problems in resistance spot welding. These problems are cracking, flush, wear of tool, distortion, overheating and melting. Because of these problems, friction stir spot welding (FSSW) became an alternative method. FSSW method has been developed for easily joining of the light metals [5]. In 2001, in the automotive industry, FSSW was developed to replace resistance spot welding for aluminum sheets [6]. This method was developed by Mazda Corporation and Kawasaki Heavy Industries in 2001 as a solid state joining technique for aluminum alloys [7]. Mazda, claims a 40% reduction in equipment investment and a 99% reduction in electricity costs compared to conventional resistance welding [8]. This new joining techniqué was also applied in transportation industries such as aerospace and automotive [9].

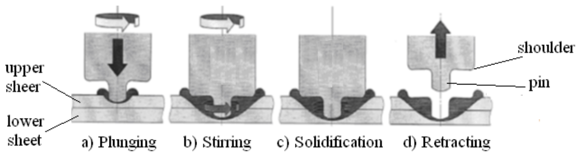

Figure 1. A schematic illustration of the FSSW process [10].

The FSSW plastics process consist of four phases; Plunging, stirring, solidification and retracting as shown in Figure 1 [10]. The process starts with the rotating of the tool. Then the tool is forced into the workpiece until the shoulder of the tool plunges into the upper workpiece. The plunge movement of the tool causes material to expel as shown in Figures 1a and 1b. When the tool reaches the predetermined depth, the plunge motion ends and the stirring phase starts. In this phase, the tool rotates in the workpieces without plunging. Frictional heat is generated in the plunging and the stirring phase and, thus, the plastic material adjacent to the tool is heated and melted. The liquid upper and lower workpiece materials mix together in the stirring phase. The shoulder of the tool creates a compressional stress on the softened material. A solid nugget forms in the solidification phase. When the temperature of the nugget falls to the predetermined degree, the process stops and the tool is retracted from the workpieces. The resulting weld has a characteristic keyhole in the middle of the joint as shown in Figure 1c.

The welding parameters and the tool material determine weld strength by affecting heat generation, stirring motion and joint formation in FSSW [8,9]. There are publications about polymer FSSW applications [11-18]. Armagan, Cevik, Oliviera, Dashatan, Bilici, Paoletti, Amancio, Chavan and Goushegir were investigated friction stir spot welding parameters, tool profile and tool design of polymers and composites [11-18]. No publication has been found on tool materials of FSSW of high density polyethylene (HDPE) and other thermoplastics sheets. Thus, this study was intended to explain the effects of the tools having different heat transfer coefficient on FSSW strength of HDPE sheets.

Taguchi method has been employed with great success in experimental designs for problems with multiple parameters due to its practicality and robustness. The Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with only a small number of experiments [19-21]. The Taguchi design method has been found to be a simple and robust technique for optimizing the welding parameters [20]. The present study is performed to fulfil the following two objectives: (1) To use the Taguchi method for determining the efficiency ratio FSSW parameters and tool materials and (2) To estimate the contribution of individual welding parameters to the strength of the FSSW weld joint.

2. Materials and Methods

In this investigation 4 mm thick high density polyethylene (HDPE) sheets were used. Polyethylene sheets were purchased from SIMONA AG, Gemany (Tensile stress 26 MPa). Figure 2 shows a lap-shear specimen that was used to investigate the weld strength of the friction stir spot welds under shear loading conditions. The specimens were welded in a milling machine. In order to develop the FSSW tests, a properly designed clamping fixture was utilized to fix the specimens deuring the welding operation. Figure 3 and 4 show a properly designed clamping fixture and welding tools used in the experiments. The tool was machined from 316 stainless steel, SAE 1020 steel, aluminum 1050 and pure copper rodes. The lap-shear test pieces were welded with identical welding parameters. The rotating tool plunged into the workpieces with a constant plunge rate to the required depth at an accuracy of ± 0.02 mm. At the beginning of each welding operation, the pin and the shoulder of the tool were cooled to the room temperature. Welded lap-shear specimens were tested on an Instron machine at a constant crosshead speed of 10 mm/s. The lap-shear fracture load was obtained by averaging the strengths of five individual specimens, which were welded with identical welding parameters.

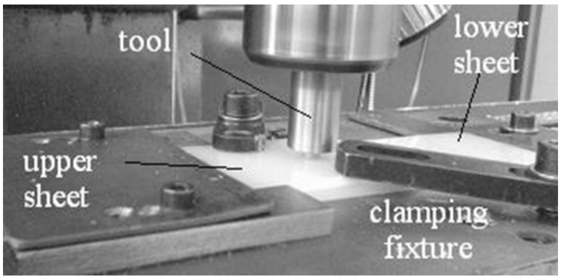

Figure 2. A properly designed clamping fixture.

(a) (b) (c) (d)

Figure 3. FSSW tools: (a) Copper (Cu), (b) SAE 1050 steel (St), (c) Stainless steel (SS), (d) Aluminum 1050 (Al)

From the preliminary experimental results, four levels of welding parameters were selected as shown in

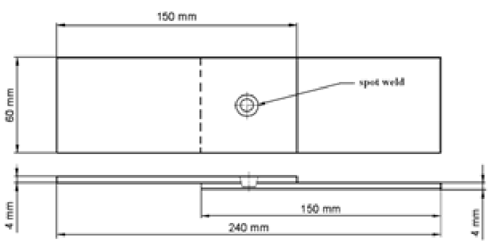

Figure 2: Configuration of the lap-shear test specimen.

Table 1. In this study an L16 orthogonal array with four columns and sixteen rows was used [22]. The experimental layout for the four welding parameters using the L16 orthogonal array is shown in Table 3. Since the L16 orthogonal array has five columns, each welding parameter is assigned to a column, and the last column is left empty for the error in experiments [22]. The orthogonality is not lost by letting one column of the array remain empty.

Table 1. Welding parameters and their level

Symbol	Welding parameter	Unit	Level 1	Level 2	Level 3	Level 4
A	Heat transfer coefficient	W/m.K°	316 Stainless steel ***(16)***	SAE 1050 steel ***(52)***	Aluminium 1050 ***(205)***	Copper ***(385)***
B	Tool rotation speed	rpm	560	710	900	1120
C	Dwell time	s	30	45	60	75
D	Tool plunge depth	mm	0.1	0.2	0.3	0.4

Table 2. Experimental layout using an L16 orthogonal array

	Welding Parameter				Error
	A	B	C	D	
Experiment number	Heat transfer coefficient ***W/m.K°***	Tool rotation speed ***rpm***	Dwell time ***s***	Tool plunge depth ***mm***	
1	16	560	30	0.1	
2	80	710	45	0.2	
3	205	900	60	0.3	
4	385	1120	75	0.4	
5	16	560	45	0.3	
6	80	710	30	0.4	
7	205	900	75	0.1	
8	385	1120	60	0.2	
9	16	560	60	0.4	
10	80	710	75	0.3	
11	205	900	30	0.2	
12	385	1120	45	0.1	
13	16	560	75	0.2	
14	80	710	60	0.1	
15	205	900	45	0.4	
16	385	1120	30	0.3	

3. Results and Discussion

3.1 Analysis of signal to noise ratio

The lap shear fracture load of designed experiments are shown in Table 3. The Taguchi method uses the signal to noise (S/N) ratio [21]. The last column of Table 4 shows the calculated S/N ratio of the experiments. The term "signal" represents the desirable value (mean) for the output characteristic and the term "noise" represents the undesirable value for the output characteristic. Therefore, the S/N ratio is the ratio of the mean to the square deviation (S.D). Taguchi uses S/N ratio to measure the quality characteristic deviating from the desired value. The S/N ratio (η) is defined as [21]:

$$\eta = -10 \log\ (MSD) \qquad (1)$$

where M.S.D. is the mean square deviation for the output characteristic.

For the spot weld strength, the higher - the better quality characteristic was taken [21]. The M.S.D. for the higher - the better quality is expressed as [21]:

$$MSD = \frac{1}{n} + \sum_{i=1}^{n} \frac{1}{T_i^2} \qquad (2)$$

Where n is the number of tests and Ti is the value of weld strength of the i'th test. The Table 3 shows the experimental results for the weld strength and the corresponding S/N ratio which were calculated by using Equations 1 and 2.

Table 3. Experimental results for weld strength and calculated S/N ratios

Experiment number	Lap-shear fracture force *N*	Calculated S/N ratio *dB*
1	537	54.59
2	2943	69.28
3	2700	68.63
4	2547	68.12
5	2813	68.98
6	2590	68.27
7	2710	68.66
8	2493	67.94
9	1340	62.54
10	2670	68.53
11	2727	68.71
12	2957	69.42
13	3117	69.87
14	3280	70.32
15	3017	69.59
16	2783	68.89

3.2 Factor and interaction effects

In these tests, sixteen different welding parameter combinations were used. Therefore, the effect of each welding parameter on the weld strength cannot be clearly understood from the result of Table 4. A minitab statistical software (Minitab 17) was used to explain the welding parameter and tool material effect [23]. From the results of Table 4, diagrams were drawn to display the welding parameters effects on the weld strength. These diagrams are shown in Figure 5. These diagrams illustrate the combined effects of any two parameters on the lap shear fracture load (LSFL). In each graph two welding parameters effect were omitted. The gray zones of the diagrams show the LSFL over 3000 N. Only two parameters can be decided by a diagram. All parameters to achieve optimum welding force should be associated with other parameters. After examining all the diagrams the obtained results were analyzed to determine the optimum welding conditions.

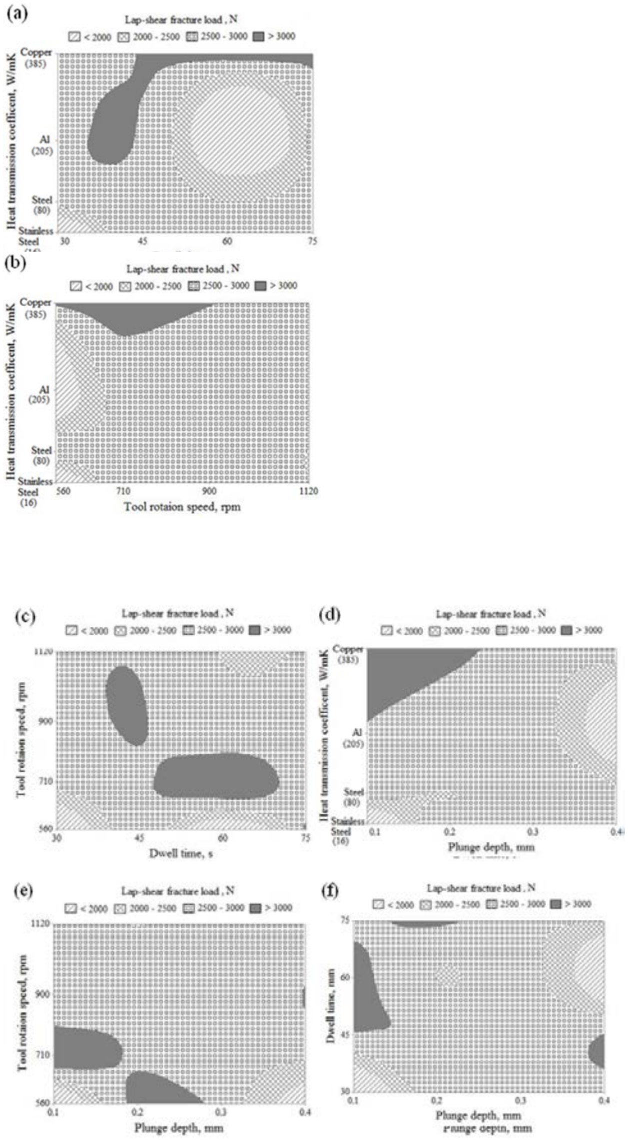

Figure 4. ANOVA analyses, the optimal welding parameters (heat transmission coefficient, tool rotational speed, dwell time and plunge depth) for lap shear fracture load

After analyzing the Figure 5 the following results were obtained: Optimum tensile strength was obtained by the welding parameters of the gray regions of the graphics. Optimum tool material was copper tool and Al. The optimum tool rotation speed varies between 560 and 1100 rpm, the dwell time lies between 35 and 75 seconds and the plunge depth must be between 0.1 and 0.3 mm. A definite optimum welding parameter combination can not be determined from these figures. All of welding parameters are required to be linked with each other. Parameters ought to be selected at regular intervals. For example, the optimum tool speed rotation, which has the biggest influence on tensile strength (33.48 %), should be selected in harmony with the other parameters. It is necessary to use only aluminum and copper tool to obtain the highest welding strength according to Figure 5 a, b and d. After one tool material is chosen the other welding parameters should be selected from the diagrams. In addition to Figure 5, S/N chart should be used to achieve optimum weld strength. Figure 5 is simply not enough alone to achieve the optimum weld strength. Therefore, figures 5 and 6 should be considered together.

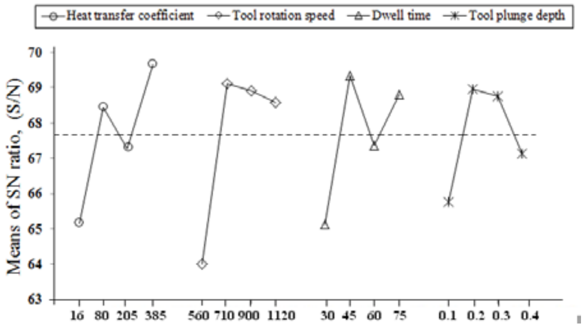

Figure 5. The mean S/N response graph for weld strength.

Table 4. S/N Response table for weld strength

Symbol	Welding parameter	Mean S/N ration dB					
		Level 1	Level 2	Level 3	Level 3	Max-min	Rank
A	Heat transfer coefficient	65.18	68.46	67.30	69.67	4.49	2
B	Tool rotation speed	64.00	69.12	68.90	68.59	5.12	1
C	Dwell time	65.12	69.34	67.36	68.80	4.23	3
D	Tool plunge depth	65.75	68.97	68.76	67.13	3.23	4

Since the experimental design is orthogonal, it is then possible to separate out the effect of each welding parameter at different levels. For example, the mean S/N ratio for tool rotation speed at levels 1, 2, 3 and 4 can be calculated by averaging S/N ratios for the experiments 1 to 4, 5 to 8, 9 to 12 and 13 to 16 respectively [19]. These results are illustrated in the first row of Table 4. Table 4 shows the mean S/N ratio for each level of the welding parameters. This table is named as the S/N response table for the weld strength. The total mean S/N ratio (ηm) of the sixteen experiments was calculated as 67.65 dB.

The S/N response graph (Fig. 6) for weld strength was drawn with using the results given in Table 4. In Fig. 6 the dashed line shows the total mean S/N ratio (67.65 dB) of the experiments. The graphs of Fig. 6 show the level effects of each welding parameter. For example, S determines the most effective parameters: Copper and SAE 1050 steel tool material, the tool rotation speed: 710- 900-1120 rpm, dwell time: 45 s-75 s and plunge depth: 0.2-0.3 mm. The weld strength decreases with the increase of the tool rotational speed and dwell time. The effect of the dwell time is similar to the effect the plunge depth. The S/N ratio is very is low at tool rotation speed 560 rpm. A1. The maximum S/N ratio is obtained at Heat transmission coefficient (Copper). The weld strength increases with the dwell time. The heat transmission coefficient and the tool rotation speed have been determined to be the most effective parameter on S/N ratio. According to Figure 6 copper tool or SAE 1050 steel tool, 710-1100 rpm tool rotation speed, 45-75 seconds dwell time , 0.2-0.3 mm plunge depth should be selected to obtain high weld strength. Figure 5 and 6 together gives the optimal welding conditions as: Copper tool, 710 rpm tool rotation speed, 45 seconds dwell time and 0.2 mm plunge depth.

3.2 Analysis of Variance (ANOVA)

The relative importance among the welding parameters on weld strength is needed to be determined so that optimal combinations of the parameter levels can be assessed accurately. The purpose of ANOVA is to find the significant factor statistically. It gives a clear picture as to how far the process parameter affects the response and the level of significance of the factor considered. The ANOVA table for signal to noise ratio are calculated and listed in Table 5. This is accomplished by separating the total variability of the S/N ratios, which is measured by the sum of the squared deviations from the total mean S/N ratio, into contributions by each of the welding parameters and the error. First, the total sum of squared deviations (SST) from the total mean S/N ratio (ηm) can be calculated as [19].

$$SST = \sum_{i=1}^{\eta} (\eta_i - \eta_m)^2 \qquad (3)$$

where n is the number of experiments in the orthogonal array and n_i is the mean S/N ratio for the i th experiment. In this study n was equal to sixteen. The total sum of spared deviations SST was decomposed into two sources: The sum of squared deviations (SSd) due to each design parameter and the sum of squared error (SSe). The percentage contribution ρ by each of the design parameters in the total sum of squared deviations (SSd) is a ratio of the sum of squared deviations (SSe) due to each design parameter to the total sum of squared deviations (SST) [21]. Statistically, there is a tool called an F test named after Fisher to see which design parameters have a significant effect on the quality characteristic. In performing the F test, the mean of squared deviations (SSm) due to each design parameter needs to be calculated. The mean of squared deviations (SSm) is equal to the sum of squared deviations(SSd) divided by the number of degrees of freedom associated with the design parameter. Then, the F value for each design parameter is simply the ratio of the mean of squared deviations (SSm) to the mean of squared error. The F test is being carried out to study the significance of the process parameter. Usually, when F>4, it means that the change of the design parameter has a significant effect on the quality characteristic in Table 5 [24].

Table 5. Results of the analysis of variance (ANOVA) for weld strength.

Symbol	Welding parameters	Degrees Freedom	Sum of squares	Mean square	F ratio	Contribution (%)
A	Heat transfer coefficient	3	19.8366	9.9183	1.57	27.74
B	Tool rotation speed	3	23.9385	11.9693	1.90	33.48
C	Dwell time	3	13.0020	6.5010	1.03	18.18
D	Tool plunge depth	3	11.6228	5.8114	0.92	16.25
Error		3	3.1059	1.5530		4.35
TOTAL		15	71.5058			100.0

4. Discussion

Table 5 shows the results of ANOVA on weld strength. The F value of a welding parameter shows the effectiveness of each parameter. The welding parameter which has the highest degree is the most important parameter [19,25]. The F value of the tool rotational speed and heat transfer coefficient are very high 1.90 and 1.57, respectively. It was found that tool rotational speed was very important in weld strength. It has the greatest F value the heat transfer coefficient was found to be second important welding parameter. The tool plunge depth was found to be the least effective factor on the weld strength, because it has the the lowest F quantity (0.92). The effects of welding parameters on weld strength are shown in Figure 6. Optimal welding parameters for weld strength over 3000 N can not be predicted precisely in Figure 6. Parameters can be estimated roughfly between intervals. However, it is possible to predict the S/N using the graphics. Once the optimal level of the design parameters has been determined, the final step is to predict and verify the improvement of the quality characteristic using the optimal level of the design parameters [21]. The estimated S/N ratio (η) using the optimal level of the design parameters can be calculated as:

$$\eta = \eta_m + \sum_{i=1}^{0} (\eta_i - \eta_m) \qquad (4)$$

where (ηm) is the total mean S/N ratio, (i) is the mean S/N ratio at the optimal level, and o is the number of the main design parameters that affect the quality characteristic.

The predicted S/N ratio using the optimal welding parameters for weld strength was determined as A4B2C2D2 (Copper tool, 710 rpm tool rotation speed. 45 seconds dwell time and 0.2 plunge depth) from S/N and ANOVA analysis (Table 4,5 and Fig 6). Five welds were produced with these welding parameters. The welds were tested and 3810 N weld breaking load was obtained. 22 % improvement was achieved by Taguchi optimization.

Table 6. Results of the confirmation experiment

	Optimal welding parameters		IMPROVEMENT
	Prediction	Experiment	
Parameter levels	A4B2C2D2	A4B2C2D2	
Fracture force (N)	3210	3810	22 %

5. Conclusions

Based on the high density polyethylene (HDPE) sheets were studied using the Taguchi method. The following results were obtained by the experimental and the analytic results.

* The L16 Taguchi orthogonal designed experiments of HDPE sheets were successfully conducted. The result of ANOVA proved that the quadratic mathematical models allow prediction of welding parameters with a 95.65 % confident interval.

* The percentage of contribution of FSSW parameters was evaluated. According to lap-shear fracture loads the tool rotation speed 33.48 %, heat transfer coefficient 27.74 % and the dwell time 18.18 % and tool plunge depth 16.25 % contributes respectively

* The tool rotation speed and heat transfer coefficient were found as dominant welding parameters.

* The optimum FSSW parameters were copper tool material, 710 rpm tool rotational speed, 45 seconds dwell time and 0.2 mm tool plunge depth. are brass.

* The improvement in the weld strength from the predicted welding parameters to the optimal welding parameters was about 22 %.

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